Optical/near-IR observations of Gamma-Ray Bursts in the Afterglow Era

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Abstract. An overview of the optical and near-IR observations of GRBs in the Afterglow Era is presented. They have allowed to a better understanding of the underlying physics as well as to constraint the progenitor models.

1 Afterglow observations

1.1 Photometric observations

Power-law declines. *BSAX* made possible to detect the first X-ray afterglow following GRB 970228 whose precise localization ($1'$) led to the discovery of the first optical transient (or optical afterglow, OA) associated to a GRB [1,2]. The OA was afterwards found on earlier images [3,4] and the light curve exhibited a power-law (PL) decay $\mathrm{F} \propto \mathrm{t}^{-\alpha}$ with $\alpha = 1.1$ [5], thus confirming the prediction of the relativistic blast-wave model [6]. PL declines have been measured for 26 OAs in 1997-2000 yielding values in the range $0.8 < \alpha < 2.3$ with $< \alpha > = 1.35$.

Breaks and steepening in light curves. A break deviating from a PL decay was first observed in the GRB 990123 light curve at $\mathrm{T}_0 + 1.5\ d$ (~ 1.5 days after the high energy event) and it was interpreted as the presence of a beamed outflow with a half opening angle $\theta_0 \sim 0.1$ [7-9], i.e. reducing the inferred energy by a factor of $\sim {\theta_0}^2/4$. Further breaks have been reported in another 5 GRBs: GRB 990510 [10-11], GRB 991208 [12], GRB 991216 [13,14], GRB 000301C [15,16] and GRB 000926 [17,18].

There are six possible explanations for the observed breaks: i) sideways expansion of the jet caused by the swept-up matter [19,20] although the effect might be negligible for $\theta_0 > 0.1$ [21]; ii) when the jet material propagates in an uniform density medium and the observer sees the edge of the jet, with α increasing by ~ 0.7 [22]; iii) when the jet material propagates in a medium with a PL density profile and the observer sees the edge of the jet, α increases by a factor of Γ^2 [22] with Γ the bulk Lorentz factor; iv) when the jet material propagates within a pre-ejected stellar wind ($\rho \propto \mathrm{r}^{-2}$) and the observer sees the edge of the jet, α increases by ~ 0.4 [22]; v) when in both the relativistic and non-relativistic cases (if ρ is high) the inverse Compton scattering is important, the light curves can be flattened or steepened [21]; and vi) when the transition

from the relativistic phase to the non-relativistic phase of an isotropic blastwave takes place in a dense medium ($\rho \sim 10^6$ cm^{-3}) [23].

Rapid fading ($\alpha > 2.0$) has been observed in 3 GRBs: GRB 980326 [24], GRB 980519 [25,26] and GRB 991208 [12]. Two possible causes can explain such behaviour: the synchrotron emission during the mildly relativistic and non-relativistic phases [23] and the interaction of a spherical burst with a pre-burst Wolf-Rayet star wind [27,28].

"Plateau" states. For GRB 970508, a "plateau" ($\alpha = 0$) was observed between T_0 + 3 *hr* and T_0 + 1 *d* [29,30]. The optical light curve reached a peak in two days [31,32] and was followed by a PL decay F $\propto$ t$^{-1.2}$. The "plateau" has been explained by several plasmoids with different fluxes occurring at different times [33]. Another "plateau" was detected in the near-IR light curve of GRB 971214 between T_0 + 3 *hr* and T_0 + 7 *hr* [34].

Short-term variability. Flux fluctuations are expected due to inhomogeneities in the surrounding medium as a consequence of interstellar turbulence or by variability and anisotropy in a precursor wind from the GRB progenitor [35]. However, short-term variability was found neither in GRB 970508 [30] nor in GRB 990510 [11]. In GRB 000301C, the high variability observed at optical wavelengths [14,15] can be due to several reasons: i) refreshed shock effects; ii) energy injection by a strongly magnetic millisecond pulsar born during the GRB [36]; iii) an ultra-relativistic shock in a dense medium rapidly evolving to a non-relativistic phase [37]; and iv) a gravitational microlens [38].

The SN-GRB association. A peculiar type Ib/c supernova (SN 1998bw) was found in the error box for the soft GRB 980425 [39] coincident with a galaxy at z = 0.0085, but this SN/GRB relationship is still under debate.

In any case, "SN-like" bumps have been detected in other GRBs: GRB 970228 [40,41], GRB 970508 [42], GRB 980326 [43,44], GRB 980703 [45], GRB 991208 [12] and GRB 000418 [46]. There are some alternative explanations for the existence of such a bump in the OA light curves: i) scattering of a prompt optical burst by 0.1 $M_\odot$ dust beyond its sublimation radius 0.1-1 pc from the burst, producing an echo after 20-30 *d* [47]; ii) delayed energy injection by shell collision [48]; and iii) an axially symmetric jet surrounded by a less energetic outflow [49]. But this is certainly not the case for all GRBs: GRB 990712 provided the first firm evidence that an underlying SN was not present [50].

1.2 Spectroscopy.

GRB 970508 was the clue to the distance: optical spectroscopy obtained during the OA maximum brightness allowed a direct determination of a lower limit for the redshift ($z \geq 0.835$), implying D $\geq$ 4 Gpc (for H_0 = 65 km s^{-1} Mpc^{-1}) and E $\geq 7 \times 10^{51}$ erg. It was the first proof that GRB sources lie at cosmological

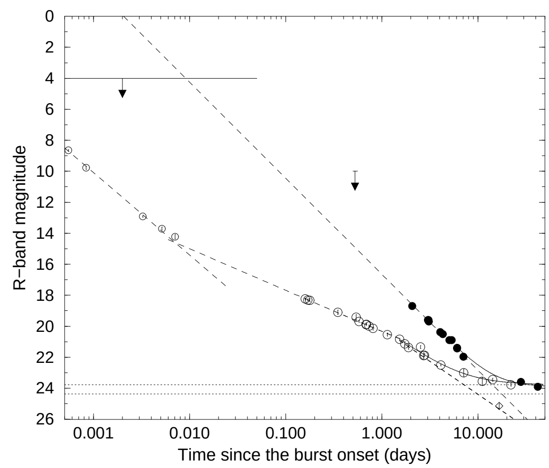

Fig. 1. The two brightest optical GRB afterglows detected so far: GRB 990123 (empty circles) and GRB 991208 (filled circles). The dotted lines are the constant contribution of the two host galaxies, R $\sim$ 23.9 and 24.3 respectively. The dashed-lines are the pure OAs contributions to the total fluxes. The solid lines (only shown here after T > 5 *d*) are the combined fluxes (OA plus underlying galaxy on each case). Upper limits are for GRB 991208. Adapted from [12].

distances [51]. The flattening of the decay at T_0 + 100 *d* [30,52] revealed the contribution of a constant brightness source -the host galaxy- seen in late-time imaging at T_0 + 1 *yr*. The 15 GRB redshifts measured so far are in the range $0.430 \leq z \leq 4.50$ [53] with $< z > = 1.5$ and they were derived either from absorption lines in the OA spectrum, from the Ly-α break, or from emission lines arising in the host galaxy.

1.3 Polarimetry.

As synchrotron radiation under favourable conditions can be up to 70 % polarized, the first polarimetric observations were attempted for GRB 990123, but only an upper limit was established ($\Pi < 2.3\%$) [54]. Polarized optical emission was first detected in GRB 990510 ($\Pi = 1.7 \pm 0.2\%$) by means of observations performed at T_0 + 18.5 *hr* [55], T_0 + 21 *hr* and T_0 + 43 *hr* [56]. This confirmed the synchrotron origin of the blast wave itself and represented another case for a jet-like outflow [11]. Further polarization measurements were carried out in GRB 990712 during a 1 *d* time interval (at T_0 + 10 *hr*, T_0 + 17 *hr* and T_0 + 35 *hr*). In that case, the polarization angle did not vary significantly but the degree of polarization was not constant [18] which can be explained by a laterally expanding jet [57]. See also [58,59].

2 Near-simultaneous GRB observations

Significant early optical emission may arise from the reverse shock [27,60], i.e. strong optical/near-IR flashes accompanying gamma-ray emission should be a generic characteristic (at least for typical GRBs, with E $\sim 10^{53}$ erg and $\rho \sim 1$ cm^{-3} [61]). Such observations will allow: i) to derive Γ by the relative timing of optical and γ-ray emission, ii) to pinpoint the process by which the shells responsible for the external shock arise, and iii) to constraint the environment.

ROTSE [62] achieved the detection simultaneously to the GRB of the bright optical emission from GRB 990123 [63]: the most luminous object ever recorded (Fig. 1), with $M_V = -36$ (peaking at $m_V = 8.9$), implying that at least some subsets of GRBs do exhibit variable optical emission as violent as the gamma-ray variations. However, upper limits (in the range R = 4-15) were derived for prompt optical emission of a dozen of bursts by means of ROTSE and other experiments, like LOTIS [64], TAROT [65], BOOTES [66,67], EON [68] and CONCAM [69]. Thus, bright optical counterparts are uncommon. Why most optical flashes are not detected? Due to several reasons: i) lack of deeper coverage, given the wide GRB luminosity function [70]; ii) fireballs in low-density environments ($\rho \ll 1$ cm^{-3}) would not be expected to produce strong prompt emission; iii) the reverse shock energy is radiated at a non-optical frequency, with the synchrotron peak frequency $\nu_m \gg \nu_{opt}$ or $\nu_m \ll \nu_{opt}$ [71]; and iv) highly absorbed GRB by dust in their host galaxies.

3 "Dark" GRBs

The first "dark" event (GRB 970828) was detected as a fading X-ray source [72], although no optical counterpart down to $m_R = 24$ at $T_0 + 4\ hr$ was detected [73]. At least in another three cases (GRB 981226, GRB 990506 and GRB 001109), radiotransients were detected without accompanying optical/IR transients. For GRB 000210, the X–ray position ($1''$ accuracy) coincides with a faint galaxy [74].

About 40% of the GRBs with X-ray counterparts do not show OAs, and this could be due to: i) intrinsic faintness because of a low ambient medium; ii) Lyman limit absorption in high redshift galaxies ($z > 7$); and iii) high absorption in a dusty enviroment: if GRBs are tightly related to star-formation, a substantial fraction of them should occur in highly obscured regions.

4 Summary

The first optical/near-IR counterparts have been found for ~ 30 precisely localized GRBs in 1997-2000 although they should have been discovered prior to the *BSAX* launch (Fig. 2). In any case, only the population of GRBs with durations of few seconds has been explored (see [76] for a more extensive review). Short bursts lasting less than 1 s, that follow the $-3/2$ slope in the log N-log S diagram (in contrast to the longer bursts) remain to be detected at longer wavelengths. Future missions should be able to address some of the issues still to be solved, i.e. prompt optical and near-IR observations should be persued !

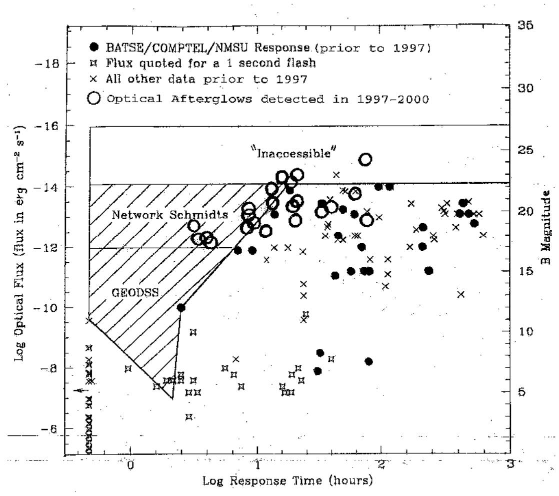

Fig. 2. The GRB follow-up response prior to 1997 (based on [75]) compared to the detection of optical counterparts in the Afterglow Era (since 1997). It is clearly seen that the fact the no optical afterglows were discovered prior to the BSAX launch was just a matter of bad luck (i.e. the ~ 10 events for which prompt deep follow-up optical searches were performed seemed to be either "rapidly-fading" or "dark" GRBs).

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